

## TEMPORAL TRACKING ON CYCLIC-INTERVAL REINFORCEMENT SCHEDULES<sup>1</sup>

NANCY K. INNIS AND J. E. R. STADDON<sup>2</sup>

DUKE UNIVERSITY

Pigeons were exposed to four cycles per session of a schedule in which the duration of successive interreinforcement intervals differed by  $t$ -sec. A cycle was composed of seven increasing and seven decreasing intervals, from  $2t$  to  $8t$  sec in length. In Exp. 1, postreinforcement pause tracked interval duration on five cyclic schedules, with values of  $t$  ranging from 2 to 40 sec. Tracking was better at shorter  $t$  values, and when discriminative stimuli signalled increasing and decreasing parts of the cycle. Pooled data for the whole experiment showed postreinforcement pause to bear a power function relationship to interval length, with a smaller exponent than the comparable function for fixed-interval schedules. Tests in a second experiment showed that pigeons trained on an arithmetic progression could also track schedules in which successive intervals followed either a logarithmic or a geometric progression, although tracking was more stable in the logarithmic case.

Cyclic-interval schedules of reinforcement (Staddon, 1964, 1967) are a form of mixed reinforcement schedule in which the same sequence of different interreinforcement intervals is presented in each experimental session. The simplest form of cyclic schedule involves intervals of only two durations. Staddon (1967) examined a two-valued schedule in which a cycle was made up of twelve 1-min intervals followed by four 3-min intervals. He found that post-reinforcement pause remained approximately constant across the four cycles making up a session. Pause duration was short, and seemed more appropriate to the 1-min than to the 3-min intervals. Other similar two-valued schedules have been studied (Kello, 1969; Innis and Staddon, 1970). In terms of overall response rate, the behavior generated by all these cyclic schedules has been similar—a higher rate during the longer intervals than during the sequence of twelve 1-min intervals. A more detailed examination of response rate across successive intervals in a cycle, however, reveals some unexpected differences. When the long inter-

vals were 2 min, rate declined across successive 2-min intervals; when they were 3 min, it remained constant; when they were 6 min, it increased. Corresponding changes in postreinforcement pause were also recorded; during the second and subsequent of a series of 2-min intervals pauses became longer, while during the second of two 6-min intervals pause decreased, and if more than two such intervals were scheduled it remained low.

In situations where successive interreinforcement intervals change progressively, rather than abruptly, changes in postreinforcement pause are not so anomalous. For example, on progressive-interval (PI) schedules (Harzem, 1969) postreinforcement pause changes systematically and in the same direction as changes in interval duration: Harzem studied schedules involving arithmetic and geometric progressions of intervals and found that rats paused longer as the duration of interreinforcement intervals gradually increased across the session.

Postreinforcement pause also comes under the control of interval duration when differential stimuli are correlated with the long and short intervals of a cyclic-interval schedule (multiple schedule). Staddon (1969) studied the behavior generated by his two-valued cyclic schedule when a red keylight was correlated with the 1-min intervals and a green keylight with the 3-min intervals. He found, in general, that postreinforcement pause was longer during the 3-min intervals, and that

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<sup>2</sup>Reprints may be obtained from J. E. R. Staddon, Dept. of Psychology, Duke University, Durham, N. C. 27706.

except for transient changes at points of stimulus change, overall response rate was similar during all intervals of a cycle.

Progressive-interval schedules differ from the two-valued cyclic-interval schedules studied by Staddon in that more than two intervals are involved in the PI case; that successive intervals are always different, and follow a progression, rather than being either the same or different, and changing abruptly; and that the change within a session is monotonic (rather than cyclic) on PI: successive intervals within the same session are either always longer or always shorter. Since there is no way of knowing which of these differences may be important for the different kinds of tracking behavior observed on PI *vs* cyclic-interval schedules, it was decided in the present study to explore further the progressive aspect by studying a cyclic schedule in which there are several different interval values that change gradually in duration across a cycle. Each cycle of the schedule used here consisted of 14 intervals, two of each of seven durations ranging in arithmetic progression from  $2t$  to  $8t$  sec. These intervals were presented in ascending and then in descending sequence during each of the four cycles of a daily session.

In a preliminary study (Innis 1970), the value of  $t$  was 15 sec. The results showed that the behavior of pigeons on this schedule can come under the control of progressively changing interreinforcement intervals; that this is most evident in the post-reinforcement pause measure; and that the addition of differential discriminative stimuli to the situation results in an increase in control of the birds' behavior by the sequential properties of the schedule, as in two-valued cyclic schedules (Staddon, 1969). Experiment 1 in the present series is a parametric extension of the earlier study, using five different  $t$ -values ranging from 2 to 40 sec. Experiment 2 consisted of a number of test sessions, and was an attempt to determine "what is learned" under these cyclic schedules.

## EXPERIMENT I

### METHOD

#### *Subjects*

Five adult White Carneaux pigeons were used: three naive (101, 103, and 104) and two birds from the preliminary study mentioned

earlier. All were maintained at approximately 80% of their free-feeding weights throughout the experiment.

#### *Apparatus*

The experimental chamber, a 14 by 12 by 13 in. (35.6 by 30.5 by 33 cm) aluminum and Plexiglas enclosure, was housed in a wooden box, covered with Styrofoam to reduce sound transmission. One of the two aluminum walls of the chamber formed a panel on which three Gerbrands clear plastic keys were mounted, 3 in. (7.62 cm) apart and 11 in. (27.9 cm) above the floor. The two outside keys were covered with cardboard. A Grason-Stadler in-line stimulus projector (stimulus series number 153), mounted behind the center key, projected the stimuli, colored lights, onto the key. A recorded response produced a loud click from a dc "feedback" relay. Four inches (10.1 cm) below the center key was a 2 by 1.75 in. (5.1 by 4.5 cm) aperture through which the birds occasionally had access to the feeder. A 10-w ac houselight illuminated the test chamber throughout the session, except during presentation of the reinforcer (3-sec, or after the one hundred fiftieth session, 3.6-sec, access to mixed grain) when the only illumination was provided by a light over the feeder. White noise and the noise of the ventilating fan helped mask extraneous sounds. Each session started with presentation of a free reinforcer.

The experiment was scheduled using an eight-channel paper-tape reader together with relays and timers. Data were recorded on digital and printing counters, and a cumulative recorder. All of this equipment was in a different room from the experimental box.

#### *Procedure*

Each cycle of the schedule involved 14 interreinforcement intervals: seven ascending (increasing in length) and seven descending. The range of interval lengths was from  $2t$  to  $8t$  sec, and successive intervals differed by  $t$  sec. Four cycles constituted a session. The five values of  $t$  on which the schedule was based were: 2 (actually 2.26), 4 (actually 4.28), 10, 20, and 40 sec. All calculations were based on the actual value of  $t$ , although the nominal values 2 and 4 are used for ease of reference. The birds' behavior was first brought to asymptote on a mixed schedule, with the key-

light amber during all intervals, and then a multiple schedule was introduced, with red and green keylights differentiating the two components (ascending and descending intervals). The behavior of each bird was studied at three different values of  $t$ . The birds were returned to the mixed schedule following sessions with the multiple schedule for the first of the three  $t$  values, but not for the second and third  $t$  values. The assignment of  $t$  values and the order of presentation was determined according to a procedure described by Edwards (1968, p. 176) for the randomization of Latin squares. Table 1 lists the order of presentation and the number of sessions at each  $t$  value for both the mixed and the multiple schedules.

### RESULTS

The major dependent variable in this experiment is postreinforcement pause. Two other possibilities—overall response rate and “running” rate—were examined, but failed to show simple relationships to the independent variables (interreinforcement time and  $t$  value).

The left panel of Fig. 1 shows postreinforcement pause for an entire session of the mixed reinforcement schedule based on each of the five values of  $t$ . Each data point is the mean for three birds over five days near the end of the mixed-schedule condition. In cases where the mixed schedule was repeated (the first  $t$  value received by each bird) the data are from the first exposure. Behavior during the

second exposure was similar in overall pattern to that observed on the initial presentation, although in absolute terms pauses were somewhat shorter for all birds. Note that the ordinate is labelled “ $t$ -sec” to indicate that each ordinate value represents the actual pause, in seconds, divided by the exact value of  $t$ . Thus, an ordinate value of 1.0 represents a pause of 4.28 sec under the  $t=4$  schedule, but a pause of 20 sec under the  $t=20$  schedule. This method of representation makes it easier to see changes in the relationship between input (schedule) and output (pause) as a function of the value of  $t$ .

Postreinforcement pause followed (tracked) the changing interreinforcement interval duration at all values of  $t$ , although tracking was “better” at shorter  $t$  values (see below). Moreover, tracking occurred throughout all four cycles of the experimental session. The average cycles in the right-hand panel of Fig. 1 show more clearly the form of the output (pause) cycles and the greater range of pause durations (in terms of units of  $t$ ) at the shorter  $t$  values.

The individual average cycles that comprise these mean average cycles are shown in Fig. 2. In general, all 15 individual cycles are similar in overall form, with changes in pause tracking changes in interreinforcement time, but tracking slightly out of phase.

In situations involving a cyclic input, the relationship between input and output cycles may be discussed in terms of phase and amplitude. If the cycles are in phase and have the

Table 1  
Presentation Order

BIRD	SCHEDULE	1		2		3	
		$t(sec)$	DAYS	$t(sec)$	DAYS	$t(sec)$	DAYS
101	MIX	10	50 (20)	4	25	40	33
	MULT		31		24		18
103	MIX	40	50 (20)	10	25	2	33
	MULT		31		24		17
36	MIX	4	50 (19)	2	25	20	33
	MULT		31		24		17
437	MIX	20	50 (19)	40	26	10	33
	MULT		31		23		17
104	MIX	2	50 (19)	20	23	4	31
	MULT		31		23		17

Order of presentation of the reinforcement schedules, based on five values of  $t$ , and the number of sessions each bird received at each  $t$ -value on both the mixed (MIX) and multiple (MULT) schedules. The number of days in parentheses for the schedule presented first is the number of sessions received on the second exposure to the mixed schedule.

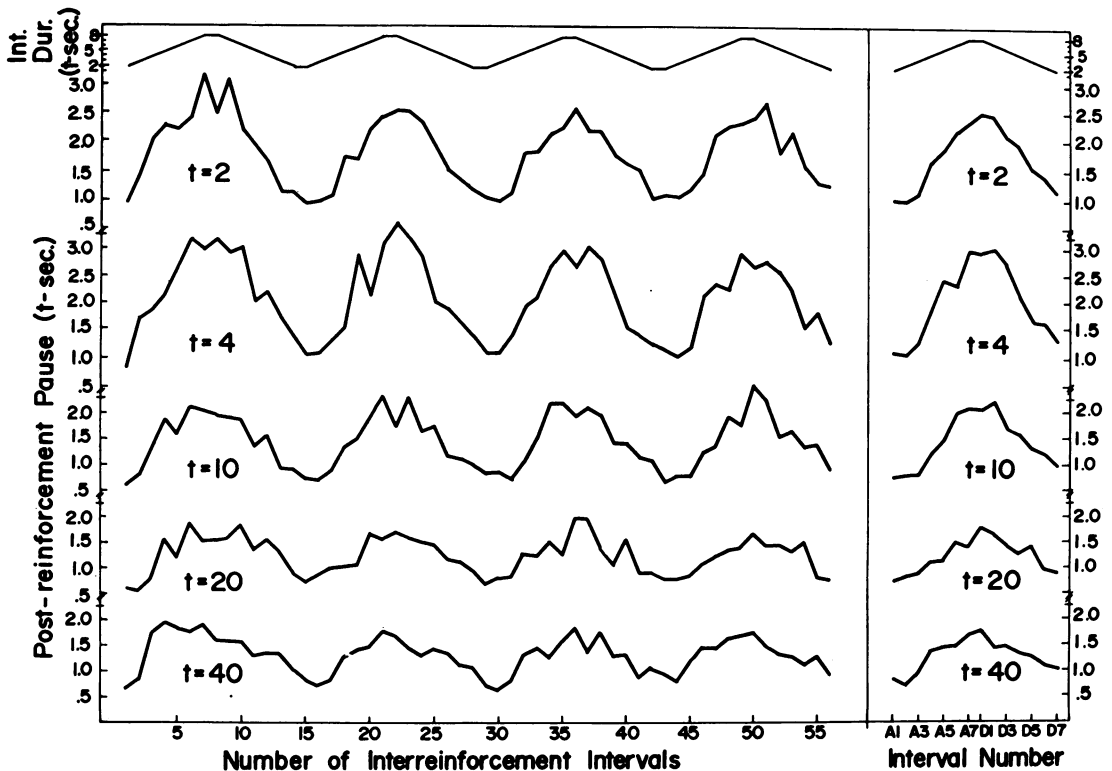


Fig. 1. Mean postreinforcement pause during each interval of the experimental session on the mixed schedule for all values of  $t$ . Each point is the mean for three birds over five days near the end of the mixed-schedule condition. At the right are average cycles—means of the last three cycles of the average session to the left. Note that the ordinate is in units of  $t$  seconds; that is, the actual postreinforcement pause in seconds has been divided by the actual value of  $t$ . At the top of the figure is a schematic representation of the changes in interval duration across the session.

same amplitude, the output may be said to track the input perfectly. Under most conditions, however, tracking is not perfect; the cycles may be out of phase, have different amplitudes, or, more probably, both. Here, the reinforcement schedule provided a cyclic input to the pigeon, whose behavioral output, as measured in terms of postreinforcement pause, was also cyclic. As Fig. 1 shows, on the mixed schedule the pause cycle tended to lag one or two intervals behind the schedule cycle, with the longest pause usually occurring in the first or second descending interval, the shortest during the first or second ascending interval. Pauses tended to be shorter, relative to the duration of the interreinforcement intervals, when the schedule was based on a large value of  $t$ . Also, the relative difference between the longest and shortest pause of a cycle (the amplitude of the pause cycle) was greater on schedules where the value of  $t$  was 10 sec or less. The amplitude of the

cycle was also greater, for all values of  $t$ , when discriminative stimuli differentiated the ascending from the descending series of intervals.

Figure 3 shows the amplitude data in more detail. The difference between the longest ( $P_{MAX}$ ) and the shortest ( $P_{MIN}$ ) pause in each average cycle is expressed as a fraction of the corresponding difference between the longest and shortest intervals of the cycle of interval durations, and plotted as a function of the value of  $t$ . The value of this function would be 1.0 if the postreinforcement pause was always exactly equal to the duration of the corresponding interval. Of course, the pause was always considerably less than the interval duration, so that the relative amplitude measure in Fig. 3 is always less than 1.0. The figure shows relative amplitude for five days of stable responding on both the mixed and the multiple conditions at each value of  $t$ . Relative amplitude was consistently higher under

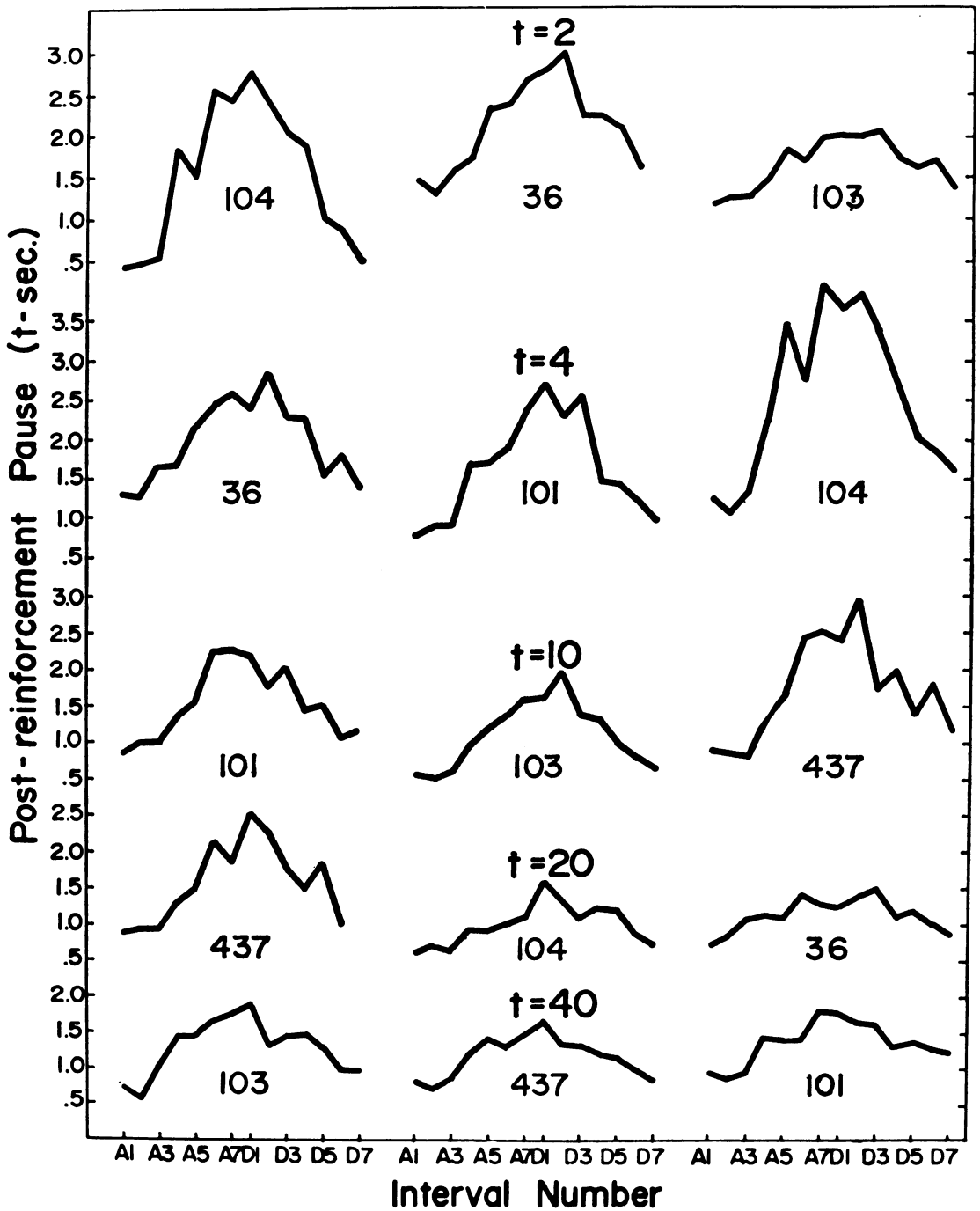


Fig. 2. Individual average cycles of postreinforcement pause for all birds for the five values of  $t$  on the mixed schedule. The data for each bird are means of the last three cycles of five sessions near the end of the mixed-schedule condition (the same five days as shown in the average data of Fig. 1). The cycles are presented from left to right for the bird receiving the schedule for his first, second, or third  $t$  value, respectively. Note that the ordinate is in units of  $t$  seconds.

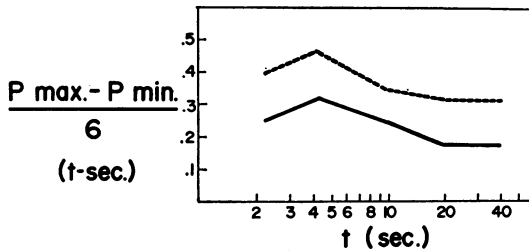


Fig. 3. Relative amplitude of the postreinforcement pause cycle as a function of the value of  $t$  for both mixed (solid lines) and multiple (broken lines) schedules. The pause data are from the mean average cycles shown in Fig. 2. The abscissa is in logarithmic units. Other details are in the text.

the multiple schedule condition, and highest at the short ( $t=4$  and  $2$ )  $t$  values.

Figure 4 shows the relationship between pause and interval length for all values of  $t$  for both mixed (left panel) and multiple (right panel) schedules. The data are plotted on log-log coordinates and, as the regression lines show, pause is related to interval length by a power function in both cases. The pauses plotted in the figure are from the 15 mean average cycles shown in Fig. 2 and from comparable data for the multiple schedule, for all the animals. If the data from each individual are considered separately, the form of the relationship is less clear, partly because the range of the independent variable is reduced in most cases (because only one bird was tested at both extreme  $t$  values).

#### DISCUSSION

The results of this experiment confirm the findings of the preliminary study—pigeons can track changes in interval duration with changes in postreinforcement pause. Temporal tracking was observed on cyclic-interval schedules in which interreinforcement intervals changed according to an arithmetic progression in increments from 2.26 to 40 sec.

The form of the relationship between interval duration and the corresponding postreinforcement pause on cyclic schedules can be compared with the form of this same relationship across simple fixed-interval (FI) schedules. If tracking were "perfect", we would expect that the length of the pause during a particular interval here would match the duration of the pause during an interval of that same value presented alone (*i.e.*, on a comparable simple FI schedule). Data from

Schneider's (1969) parametric study of fixed-interval schedules, ranging from FI 16-sec to FI 512-sec, are shown in Fig. 4 (open circles, left panel), with a straight line, fitted by eye, drawn through the points. The slope of this line is 1.0, since Schneider found that pause and interval duration are linearly related under conditions where only one interval value is scheduled during an experimental session. The slopes of the regression lines through the data from the present study are less than 1.0. It is possible that this difference is due to the slightly different postreinforcement pause measures used in these two studies. Schneider's "break" measure ignores any low-rate pecks early in the interval, whereas here pause was measured as time to the first response, whether or not the response was closely followed by others. There is no reason to assume that these two measures are not linearly related, however, and two factors suggest that they are. First, it has generally been assumed that postreinforcement pause, as measured here, comprises a constant one third to one half of the interval on fixed-interval schedules. Second, an examination of cumulative records from this study showed there were very few low-rate responses early in the intervals; once a bird began pecking it continued to respond steadily until reinforcement occurred. A more plausible explanation for the lower slopes, therefore, is that the cyclic-interval schedule places some limitation on the control of the pigeon's behavior by the temporal aspects of the situation.

Further evidence for a limitation on temporal control due to variation in interval length is provided by the fact that tracking is "better" (*i.e.*, the output cycle is closer to the input cycle in amplitude and/or phase) (1) at small values of  $t$  (*cf.* Fig. 1 and 3); and (2) when stimuli differentiate the ascending from the descending series of intervals (*cf.* Fig. 3).

#### EXPERIMENT 2

The demonstration that pigeons can "track" systematically changing interreinforcement intervals immediately raises the further question of how they do it. The tests making up the second experiment were directed to this problem, which may be broken down into a number of subsidiary questions, for example: (1) Have the birds learned some kind of general

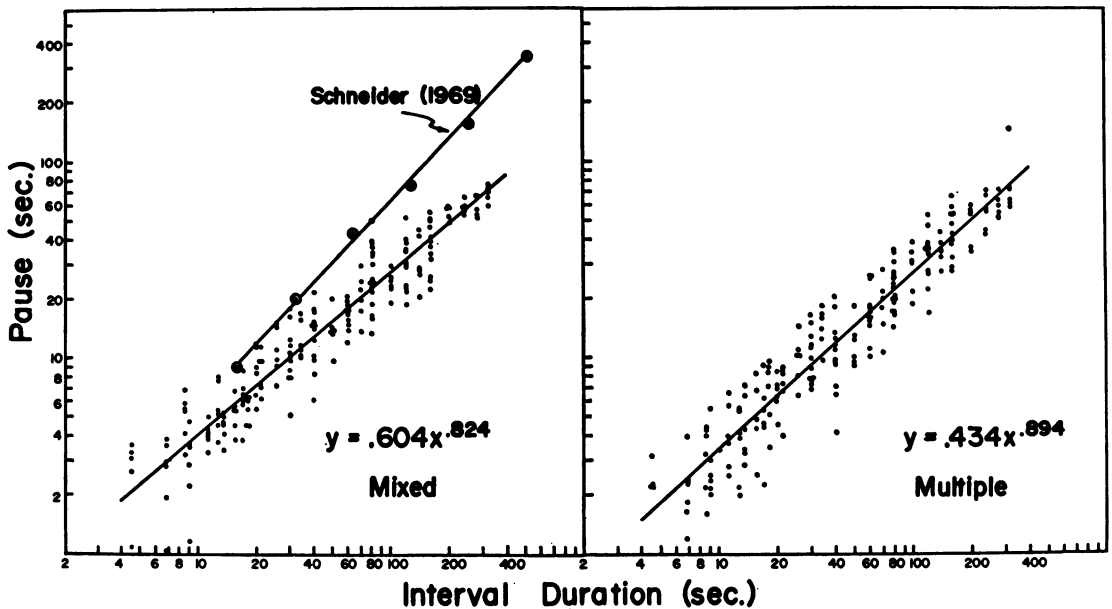


Fig. 4. Postreinforcement pause as a function of interval duration for the mixed (left panel) and multiple (right panel) schedules. Equations for the regression lines are indicated on the figure. Data from Schneider (1969) for this relationship on simple fixed interval are also included (left panel, open circles), with a straight line, drawn by eye through the points.

rule for tracking changes in interreinforcement interval, or merely something specific to the sequence of intervals used here? If they have learned something general, they should still be able to track on schedules where the sequence of intervals is considerably different from the arithmetic progression used in training. (2) Are the fluctuations in local reinforcement density resulting from the cyclic schedule the relevant controlling factor? These fluctuations are reliably related to time since the beginning of the session, and, just as variations in reinforcement density as a function of postreinforcement time can come to produce corresponding variations in local response rates (Catania and Reynolds, 1968), so the variation here might come to produce variations in pause as a function of time in the session. This possibility can be tested both by running extinction tests—the birds' response rate might be expected to vary cyclically in a similar way to their rate under the normal schedule—and by starting the regular schedule out of phase (*e.g.*, with the descending rather than the ascending part of the sequence): if time in the session is a controlling factor, relationship between schedule and responding should be disrupted by this manipulation.

## METHOD

### Subjects

The five birds used in Exp. 1 were maintained at 80% of their free-feeding weights throughout this experiment.

### Apparatus

The apparatus was the same as that used in Exp. 1.

### Procedure

All birds received identical treatment throughout the experiment. In order to provide a baseline with which the behavior during the various test conditions could be compared, the birds were given 18 sessions on the same  $t=10$  cyclic-interval schedule used in Exp. 1 (mixed schedule, amber keylight). Following these training sessions were nine test sessions, each of which was separated from other test sessions by at least three sessions of the  $t=10$  schedule. During most of the tests, the regular  $t=10$  schedule provided a baseline to which various test intervals or cycles were added. As before, each session started with a free reinforcer.

The nine test sessions occurred in the following order:

*Test 1—extinction.* At the end of the first cycle of the session a 20-min extinction period occurred, replacing the first interval (A1, 20 sec) of the second cycle. It ended with a response-contingent reinforcement, which placed the bird in the second ascending interval (A2), a 30-sec interval. The rest of the session continued on the regular  $t=10$  schedule.

*Test 2—extended cycle.* This test session was composed of five cycles. The first and last of these were regular cycles of the  $t=10$  schedule; the middle three were test cycles. Each test cycle consisted of 18 intervals, nine in the ascending and nine in the descending series, changing in duration from  $2t$  to  $10t$  (and then  $10t$  to  $2t$ ), with  $t=10$  sec. Thus, each test cycle was a regular cycle extended in the same arithmetic progression by two more intervals.

*Test 3—flat top.* As in the previous test, a session consisted of five cycles; the first and last, regular 14-interval cycles of the  $t=10$  schedule; the middle three, test cycles. Each test cycle consisted of 18 intervals, the regular  $2t$ - $8t$  series and four extra  $8t$  intervals at the top of the cycle. Thus, the following series of interval durations occurred in each test cycle: 20, 30, 40, 50, 60, 70, 80, 80, 80, 80, 80, 70, 60, 50, 40, 30, and 20 sec.

*Test 4—flat top and base.* This test schedule was similar to the schedule for Test 3; however, as well as the four additional 80-sec intervals, two  $2t$  (20-sec) intervals were added to both the beginning of the ascending series and the end of the descending series during the three test cycles. Each test cycle consisted of the following sequence of 22 intervals: 20, 20, 20, 30, 40, 50, 60, 70, 80, 80, 80, 80, 80, 80, 70, 60, 50, 40, 30, 20, 20, and 20 sec.

*Test 5—geometric progression.* During this test the rule specifying the distribution of interreinforcement intervals during a cycle was changed. The total cycle-time, 700 sec, and the number of reinforcements per cycle, 14, remained the same as under the  $t=10$  (arithmetic progression) schedule. The seven different interval values were presented in ascending and descending sequence during each of the four cycles of test session. In order to satisfy these criteria, interval values were determined by the following equation:  $t + \theta t +$

$\theta^2 t + \theta^3 t + \theta^4 t + \theta^5 t + \theta^6 t = 350$ , which yields  $t=2.76$  and  $\theta=2.0$ . Thus, the nominal values of the geometric sequence of intervals were: 3, 6, 11, 22, 44, 88, and 176 sec. Due to the properties of the timer arranging this series the actual interval values were: 3.39, 6.78, 12.4, 24.9, 49.7, 99.4, and 198.9 sec. Thus, the total cycle time was actually about 91 sec longer than during the regular  $t=10$  schedule.

*Test 6—reverse cycle, geometric progression.* The same sequence of intervals (geometric progression) as in the previous test was presented, but in the reverse order. The session started with the longest interval of the descending series, rather than the shortest ascending interval. Four cycles were presented during the session, which ended with interval A7, the longest interval of the ascending series.

*Test 7—reverse cycle, arithmetic progression.* The regular  $t=10$  schedule was presented, but the session started with the first interval of the descending series of cycle one, D1, and 80-sec interval. The session consisted of three and one half cycles, and ended as usual at the end of the descending series of the fourth cycle.

*Test 8—logarithmic progression.* This test also provided a new rule for determining the changes in interreinforcement time across a cycle. As with Test 5, the number of reinforcements per cycle remained at 14, and the period of the cycle at 700 sec, the same as in the regular schedule. The nominal values of the intervals, which changed according to a logarithmic progression were: 18, 38, 47, 55, 60, 65, and 69 sec. This sequence was determined by the following equation:  $\log_{10} x + \log_{10} 2x + \log_{10} 3x + \log_{10} 4x + \log_{10} 5x + \log_{10} 6x + \log_{10} 7x = 5.822$ , which yields  $x = 2.01$ . If each term in the equation is multiplied by 60.0, the total is 350 sec, the number of seconds in half a cycle. The actual values of the intervals, again slightly longer than the nominal values, were: 20.3, 40.7, 53.1, 62.2, 67.8, 73.5, and 78.0 sec.

*Test 9—extinction.* As with the first extinction test, a 20-min extinction period was interpolated into the regular  $t=10$  schedule. During this test it replaced the first descending interval (D1, 80-sec) of the second of the four cycles of the session. It ended with a response-contingent reinforcement and was followed by the second interval of the descending sequence, D2, a 70-sec interval.



## RESULTS

Figure 5 presents cumulative records from the two extinction tests (Tests 1 and 9). The data are from two birds, Bird 103, top two records, and Bird 437, lower two records. The intervals preceding and following the extinction period are shown. The upper record for each bird is from Test 1, the lower, from Test 9. These particular data were chosen because they represent the two extremes of responding observed during the extinction periods. Bird 103 responded at a fairly constant rate throughout the entire 20 min, while Bird 437 showed a cyclic variation in rate. The responding of the other three pigeons fell between these two extremes. Data from the two extinction periods, separated by 42 days, were similar in form across individual birds; and, as the figure shows, the periodicity in Bird 437's responding is almost in phase in the two extinction sessions.

Figure 6 presents the data from Tests 2, 3, and 4, in which the regular  $t=10$  schedule was modified by the addition of extra intervals. On the left in the figure is an average cycle of response rate and postreinforcement pause from the baseline  $t=10$  schedule, included for purposes of comparison. These baseline cycles are means across the five birds for the last three cycles of the session on the day preceding Test 2. The average cycles for Test 2, shown in the center of the figure, and for Tests 3 and 4, on the right, are means of the five birds across the three test cycles on each test. A schematic profile of the changes in interval duration across the cycle is shown for each schedule. As Fig. 6 shows, behavior during all three tests was very similar to that observed under the baseline conditions. The longest postreinforcement pause typically occurred during the second presentation of the longest interval, while during Tests 3 and 4 it was in the second of the six 80-sec intervals. The baseline cycle presented in this figure is unusual in this respect, with the longest pause during the first 80-sec interval. Usually during training sessions pause was longer in interval D1 than in interval A7. During Tests 3 and 4, where many intervals of the same duration were scheduled, pause was also fairly constant for several intervals, with the tracking still one or two intervals out of phase with the input cycle.

During Tests 5 and 8, the rule determining the temporal distribution of reinforcements across a cycle was changed. Figure 7 shows both response rate and postreinforcement pause data for the entire session of Test 5, geometric progression, in the top half of the figure, and Test 8, logarithmic progression, at the bottom. The data from Test 5 are the means for four birds, since data for Bird 103 are not available (due to an equipment failure). The data for Test 8 are the means for all five birds. At the right in the figure are average cycles, means of all the four cycles presented on the left. Between the response rate and pause cycles a schematic profile of the changes in interval duration is shown. As is shown in the figure, the mean average cycles, especially for the geometric schedule, are not entirely representative of the individual average cycles which they comprise.

Postreinforcement pause on the logarithmic schedule tracked the schedule changes, and on the average was similar in form to the baseline schedule pause cycle. As the average cycle of Fig. 7 shows, however, pauses were generally longer during the later intervals of the ascending series during this test condition, than during these same intervals on the arithmetic schedule. On the geometric schedule, the form of the postreinforcement pause cycle changed across the four cycles of the session. The initial shortest pause, during the first cycle, was about 10 sec in duration, as was observed on the baseline schedule. After experience with the first few very short intervals of the geometric series, however, the shortest pause in a cycle dropped to about 5 sec and remained at this level throughout the rest of the session. This change was quite persistent; the average shortest pause remained at about 5 sec for a number of subsequent sessions. By the final cycle of the geometric test session, most pauses during the cycles were short.

During Test 6, when the geometric schedule started with the longest interval of the descending series, the behavior was similar to that observed on the first geometric test (Test 5). Similarly, when the arithmetic series was presented half a cycle out of phase with the training schedule (Test 7), the behavior did not differ from that observed during a regular training session.

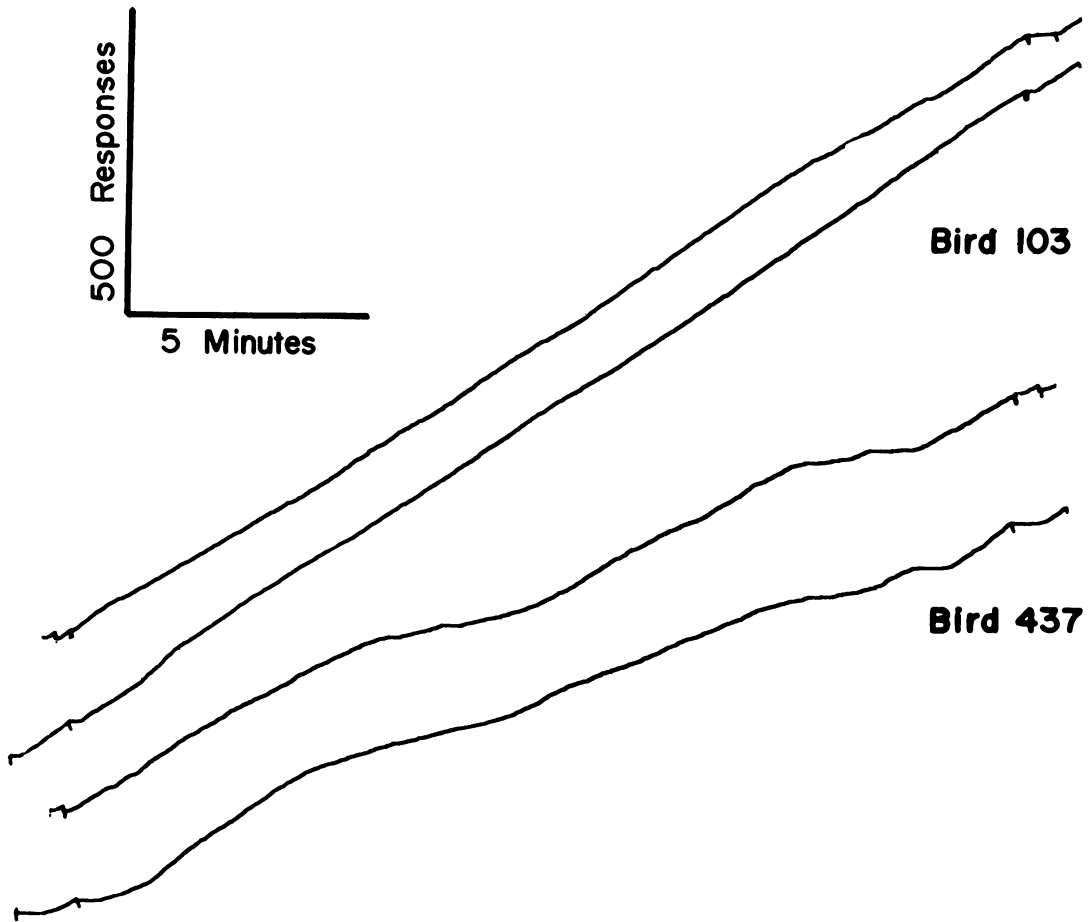


Fig. 5. Cumulative records for Bird 103 (top two records) and Bird 437 (bottom two records) during the 20-min extinction periods of Test 1 (upper record) and Test 9 (lower record). Also included are the intervals immediately preceding and following extinction. Blips on the record indicate reinforcements.

#### DISCUSSION

The behavior of the pigeons during these test sessions permits some conclusions about the factors underlying the temporal tracking observed on cyclic-interval schedules. The hypothesis that the birds have learned to respond cyclically as a function of session-time so as to match the cyclic variation in reinforcement density on the training schedule, predicts that the cyclic output across the session during a test should be similar to that obtained on the baseline schedule. During Test 7, when the input cycle was started out of phase, this would mean that the postreinforcement pause cycle should be half a cycle out of phase with the input. The test showed, however, that after the first few intervals the birds' postreinforcement pauses had the same

phase relationship with the input cycle as did the pauses on the training schedule; the longest pause was during interval A7 (80 sec), the shortest in interval A2 (30 sec) (see Fig. 6, left panel). The behavior during the two 20-min extinction periods was almost identical, as the records for the two birds in Fig. 5 show, and only the data of Bird 437 showed extensive cyclicity. As well as predicting cyclic behavior during extinction, this hypothesis would also predict that the cycles would be out of phase during the two extinction intervals, which were interpolated at different points in the cycle. In fact, as Fig. 5 shows, the two extinction cycles for Bird 437 are almost entirely in phase. As a result, cyclic variation in responding as a function of session time can be rejected as a major factor (*cf.* Staddon, 1967).

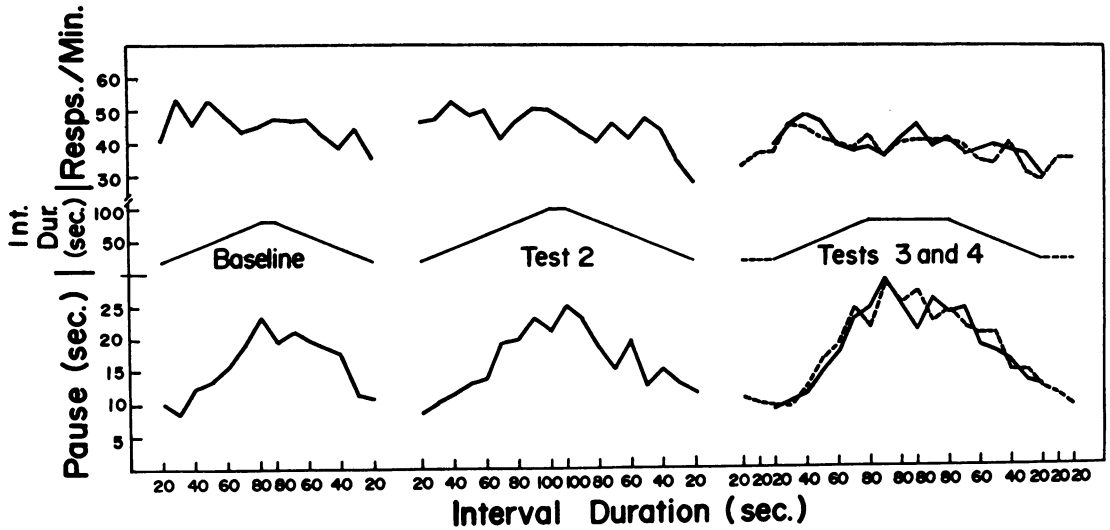


Fig. 6. Mean average cycles for response rate and postreinforcement pause from the baseline  $t = 10$  schedule (left), Test 2 (center), and Tests 3 and 4 (right). The data for Test 3 are plotted in solid lines; for Test 4 in broken lines. The data from the baseline condition are the means for five birds over the last three cycles of the session on the day before Test 2. Test data are means of five birds over the three test cycles of each test session. A schematic representation of changes in interval duration across a cycle is shown for each condition.

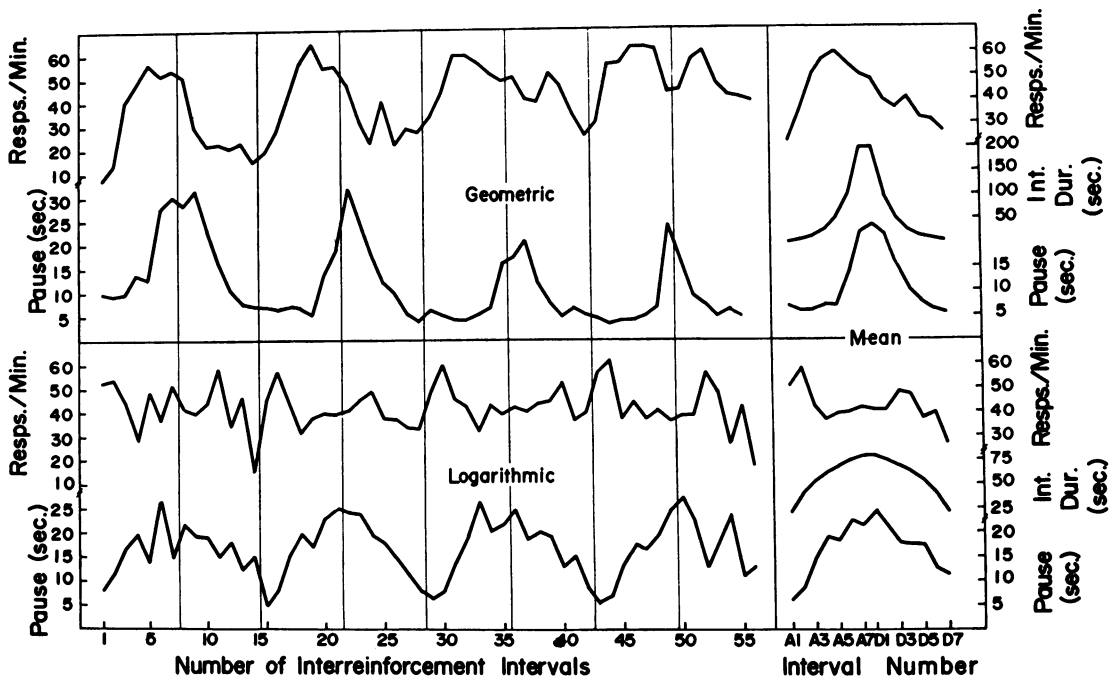


Fig. 7. Response rate and postreinforcement pause during each interval of Test 5 (top), geometric schedule, and Test 8 (bottom), logarithmic schedule. Each point for Test 5 is the mean for four birds (excluding 103), and for Test 8 for all five birds. To the right are average cycles, means of all four cycles shown to the left. Between the average cycles for pause and rate for each schedule, a schematic representation of the changes in interval duration across a cycle of the schedule is shown.

The data from tests when the arithmetic schedule of the baseline procedure was modified by the addition of extra intervals, and from tests in which a different series of interreinforcement intervals was presented, all indicate that the birds had acquired an ability to track systematically varying interreinforcement intervals that generalized beyond the specific sequence under which it had been learned. Thus, the behavior on the geometric schedule was clearly different from baseline performance. The changes were not as extensive during the logarithmic test, but this schedule is similar to the baseline schedule; the shortest interval is 20.3 sec, as compared to 20 sec on the arithmetic schedule; the longest interval 78 sec, as compared to 80 sec.

Figure 7 shows that the tracking performance during the geometric test sessions deteriorated through the session. This partial breakdown suggests that the gradualness of the change from one interreinforcement interval to the next is probably an important contributor to tracking performance, both here, and on progressive-interval schedules, because the geometric schedule, although progressive, involved quite substantial changes in interval length at some points in the cycle. Thus, the profile of the input cycle, shown in the right panel of Fig. 7, shows that the geometric sequence is intermediate between the arithmetic training schedule, which produced tracking, and the "square wave" profile of the two-valued cyclic-interval schedules used previously (Staddon, 1967), which produced no tracking by postreinforcement pause. This inference is supported by the results from the test with the logarithmic schedule, which, like the arithmetic training schedule, involved only gradual changes in the length of successive intervals, and which showed better and more stable tracking than the geometric schedule.

On simple fixed-interval schedules it is possible to point to a single environmental event, such as food presentation, whose occurrence fixes the time of onset of responding within each interval: in the steady state, pigeons start to peck at an approximately fixed time following reinforcement (if reinforcement initiates the fixed interval). There is obviously no single event that determines the time of onset of pecking under these cyclic interval schedules. However, it is of some in-

terest to discover what property or properties of the antecedent sequence of intervals determines the time of onset of pecking in a given interval.

Behavior in a given interval may be determined by events associated either with a few preceding intervals, or with all the preceding intervals in a given session. However, the latter possibility suggests that responding should change markedly and systematically across a session, and Fig. 1 shows that this was not generally the case. There is reason to suspect, therefore, that the steady state behavior in a given interval is affected by a relatively small number of preceding intervals. Unfortunately, it is difficult to assess the relative contribution of preceding intervals to postreinforcement pause during a given interval, and data from the extinction tests suggest that this relationship may not be a simple one. If, for example, absolute interval duration were the most important factor, and the pause in interval  $n$  was determined largely by the preceding interval, then the behavior following extinction (a very long interval) should reflect this. A very long pause would be expected in the interval following extinction, and perhaps in subsequent intervals. Long pauses were observed following the first extinction period (Test 1), but the mean pause was about 31 sec—little different from 25 sec, the average longest pause during training. The average pause following the second extinction period (Test 9), was in fact shorter than the average longest pause of a cycle. This result suggests that there is a ceiling on the longest pause. The data from Test 2 support this idea to some extent. In this test, the regular arithmetic series was extended by two intervals so that the longest interval of the cycle was 100 sec rather than 80 sec. Under these conditions the birds tracked the schedule changes with changes in pause; however, the longest average pause remained at about 25 sec, while pauses during the 80-sec intervals of this test session were shorter than during 80-sec intervals of the baseline schedule.

As well as an upper limit on pause duration, the birds seem to establish a lower limit, based on the shortest interreinforcement time; here it is 10 sec, half the shortest (20-sec) interval. This might be expected from data presented by Catania and Reynolds (1968) where on a random mixed-reinforcement

schedule, the postreinforcement pause is determined by the shortest interreinforcement time. In the present experiment this lower limit was quickly changed when a new schedule, with much shorter interreinforcement intervals, was presented on only two occasions (the geometric schedule, Tests 5 and 6). Following the first few intervals of the geometric schedule, the shortest pause decreased to 5 sec (see upper panel, Fig. 7), and when the birds were returned to the baseline schedule it remained at about 5 sec for many sessions.

In summary then, the tests indicate that two factors seem to be involved in the tracking observed on the baseline schedule. (1) A limiting range of postreinforcement pause was established. Both the changes in pause following exposure to the geometric test schedule and the findings of Catania and Reynolds (1968) support the view that the shortest pause was determined by the shortest interreinforcement interval of the schedule. Moreover, once it was established it was relatively persistent. The behavior during extinction tests and tests that added to or extended the intervals of the arithmetic series indicates that a longest pause was also established. This longest pause may depend on both the shortest and longest intervals of a cycle. The parametric data from Exp. 1 suggest that this longest pause may be a larger proportion of the longest interreinforcement interval on schedules based on a low value of  $t$ . (2) There is also evidence for a generalized tracking process relating the bird's behavior in interval  $n$  to some property of preceding intervals (*e.g.*, interval length, number of responses made, *etc.*). Data

from the geometric test support this assumption. This second factor appears to operate within limits set by the first factor.

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